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Analysis systems for the mesoscale  
thermal variability in the  
Greenland-Iceland-Norwegian Sea

D. Grillaki-Steiert  
and V. Amoroso

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**Analysis systems for the mesoscale thermal  
variability in the Greenland-Iceland-Norwegian  
Sea**

D. Grillaki-Steiert and V. Amoroso

**Abstract:** Mesoscale thermal structure and its spatial variability are very significant for acoustic propagation in the ocean. Therefore ocean thermal analysis procedures are important for the initialisation and verification of environmental and acoustical models. This study involved the implementation of software, and the production, from irregularly-spaced data, of uniformly-gridded temperature fields for use by numerical acoustical and environmental models. The two analyses, considered for the production of temperature fields are: (1) an objective analysis method based on the Gauss-Markov Theorem which makes use of additional information such as climatology (the Levitus climatology has been used in this study), and (2) an interpolation method based on contouring techniques provided by the UNIRAS graphics package. Data from the Summer '86 cruise in the Greenland-Iceland-Norwegian Sea of the Applied Oceanography Group of SACLANTCEN are used to demonstrate the methods. Both methods agree well when there is a high density of data. When the data availability is limited, there is a danger that the objective analysis method can give rise to spurious gradients in going from the regime dominated by data to that dominated by climatology. Whether this is less desirable than a field based on extrapolation from a few observational data points depends on the application.

**Keywords:** acoustic propagation    ◦    Gauss-Markov theorem    ◦  
Greenland-Iceland-Norwegian Sea    ◦    Levitus climatology    ◦    modelling    ◦  
oceanography    ◦    thermal analysis    ◦    thermal variability

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## 1. Introduction

Oceanographic and acoustic numerical models require a synoptic (instantaneous) picture of the ocean thermal field. The development and operational use of range-dependent acoustic models is dependent on the information provided by such an ocean thermal field. However the simultaneous collection of the uniformly-spaced oceanographic samples required for the synoptic description of a thermal field would be too expensive to realize in practice. Satellite data could be used to provide a synoptic picture of the surface thermal field but they cannot directly give any information on the thermal field below the surface.

In this work an objective analysis method and a contouring analysis method have been used to transform irregularly-spaced data to uniformly-gridded fields for use by numerical oceanographic and acoustic models. This involved two distinct tasks:

- (1) The implementation of software to adapt the objective analysis system to the Greenland-Iceland-Norwegian Sea (GIN Sea) area, and to interface it with an oceanographic database and the commercially-available graphics package UNIRAS. Also to interface the UNIRAS contouring system to the oceanographic database.
- (2) The production of two-dimensional high-resolution ( $0.5^\circ \times 0.5^\circ$ )-gridded thermal data fields of the GIN '86 data (i.e. data from the Summer '86 cruise of the SACLANTCEN Applied Oceanography Group in the GIN Sea) with the two methods, for input into oceanographic or acoustical range-dependent models.

## 2. Data

### 2.1. SAMPLED DATA SETS

The data used in this study are 92 CTD profiles obtained using a Neil Brown Instrument Systems Conductivity-Temperature-Depth profiler. Temperature data sets, for depth levels of 10, 50, 100, 150 and 200 m, were extracted from an oceanographic database and used to initialise, together with the Levitus climatology, the objective analysis programs, or were interfaced directly with the UNIRAS package for the production of two-dimensional high-resolution thermal fields.

A data table, or data set, is created after a database search that has imposed some selection criteria on the stored data files.

For the GIN Sea data set display a formatted column representation was used: the first two columns contain the longitude and latitude of the sampled data, and the remaining columns give the required oceanographic physical parameters.

### 2.2. LEVITUS CLIMATOLOGICAL DATA

The Levitus climatology (1982) is a synthesis of all temperature salinity and  $O_2$  data available at NODC (National Oceanographic Data Centre) analysed in a consistent objective manner on a  $1^\circ \times 1^\circ$  grid between the surface and ocean bottom at standard ocean analysis levels. Annual and seasonal analyses have been computed. The analyses comprised all data regardless of the year of observation (running from the late 1940's to the first quarter of 1978). The spring Levitus temperature climatological data for our area of interest have been used together with the GIN '86 data to initialise the objective analysis programs.



### 3. Database

The two methods, objective analysis and contouring analysis, used 92 CTD profiles (Fig. 1) averaged over 10 m intervals from the Summer '86 cruise in the Greenland-Iceland-Norwegian Sea. An oceanographic environmental database has been developed at SACLANTCEN in the Applied Oceanography Group (AOG) for the storage of oceanographic and meteorological data collected by SACLANTCEN or other oceanographic institutes. Before ocean environmental data are loaded into the AOG database they are submitted to data-processing by a system that checks acquisition and data quality (see Fig. 2a). Extraction of stored data sets and other operations on the database are made by a database search (see Fig. 2b), which follows some selection criteria, and results in a collection of files containing the required oceanographic data sets.

After a database search two options can follow:

- Operations on data files, changing existing data sets.
- Data table generation, i.e. generation of data sets. (This option has been interfaced with the UNIRAS graphics package.)

#### 4. Interpolation methods

##### 4.1. OBJECTIVE ANALYSIS METHOD

Objective analysis theory, sometimes referred to as optimal estimation, was first developed for application to meteorological data by Gandin (1963). The objective analysis method used here is a variant of the optimum interpolation method developed by Bretherton Davis and Fandry (1976) for ocean forecasting and has been modified for the GIN Sea. The method interpolates irregularly-spaced observations to a regular grid. It is a powerful statistical interpolation technique that uses calculated field statistics, i.e. cross-correlation between data points, to calculate an estimated uniformly-gridded field extending to locations where few or no data exist. This estimated field is such that it minimises, in a least-squares sense, the difference between itself and an ensemble of the observed fields. Given  $N$  observations of data  $D_i$  at different locations  $x_i$ , a simple linear estimate of the true field  $F_0$  at some other point  $x_0$ , which can be a grid point, is

$$\hat{F}_0 = f_0 + \sum_{i=1}^N a_i (D_i - f_i), \quad (1)$$

where  $\hat{F}_0$  is the estimated field at grid point  $x_0$ ,  $f_0$  is a first-guess field at grid point  $x_0$  (i.e. the value of the climatological field at a grid point), and  $f_i$  is a first-guess field at points  $x_i$  (i.e. the values of the climatological field at the measured data positions).

The  $a_i$  are coefficients and are derived using the following scheme. According to the Gauss-Markov theorem the minimisation of the expected squared error  $E_0^2$  is

$$E_0^2 = \langle (F_0 - \hat{F}_0)^2 \rangle, \quad (2)$$

where  $\langle \dots \rangle$  is the statistical expectation or ensemble mean.

Considering the deviation of the above fields from the first-guess or climatological field when  $d_i = D_i - f_i$ ,  $f_0 = F_0 - f_0$ :

$$\begin{aligned} E_0^2 &= \langle [(F_0 - f_0) - (\hat{F}_0 - f_0)]^2 \rangle \\ &= \langle (f_0 - \sum_{i=1}^N a_i d_i)^2 \rangle \\ &= \langle f_0^2 \rangle - 2 \sum_{i=1}^N a_i \langle f_0 d_i \rangle + \sum_{i=1}^N \sum_{j=1}^N a_i a_j \langle d_i d_j \rangle. \end{aligned} \quad (3)$$

Minimising  $E_0$  with respect to  $a_i$ ,  $\partial E_0 / \partial a_i = 0$ , gives a set of  $N$  linear equations for  $a_i$ ,

$$\sum_{i=1}^N a_i \langle d_i d_j \rangle = \langle f_0 d_j \rangle, \quad (4)$$

which can be used to calculate the  $a_i$ , if the statistical properties of the field  $\langle d_i d_j \rangle$  and  $\langle f_0 d_j \rangle$  are known. The  $\langle d_i d_j \rangle$  is the covariance of observational data with itself and  $\langle f_0 d_j \rangle$  the covariance between the true field, at a grid point, and the observations. These are functions of distance and can be estimated from the correlation function of the observations, or can have some imposed functional form. In our study, in line with experience gained at NORDA (P. May, personal communication), they have been given the form

$$\langle d_i d_j \rangle = \exp [-(a |x_i - x_j| + b |y_i - y_j| + c |z_i - z_j|)], \quad (5a)$$

$$\langle f_0 d_j \rangle = \exp [-(a |x_0 - x_j| + b |y_0 - y_j| + c |z_0 - z_j|)]. \quad (5b)$$

The constants  $a$ ,  $b$  and  $c$  are chosen based on the data and a physical understanding of the processes involved. In our case we resort to external observations and estimate these values to be  $a = (50 \text{ km})^{-1}$ ,  $b = (50 \text{ km})^{-1}$ ,  $c = (0.5 \text{ km})^{-1}$ . They are the reciprocals of eddy length scales in  $x$ ,  $y$ , and  $z$  direction of our area of interest.

Equation (4) is of the form

$$CX = D, \quad (6)$$

where  $C$  is the positive-definite symmetric matrix with the correlations of all observational pairs (Eq. (5a)),  $D$  is the vector with the correlations between the grid points and observational data (Eq. (5b)), and  $X$  contains the values of the coefficients which minimise the error, which are to be determined. For the inversion of matrix  $C$  we used a Cholesky factorisation followed by forward and backward solution (for more details, see Grillaki, 1988).

The associated error field  $e_0$ , for the estimated field  $\hat{F}_0$ , is given by the equation

$$e_0 = 1 - \sum_{j=1}^N a_j \langle f_0 d_j \rangle. \quad (7)$$

The objective analysis method, including a full derivation of these equations, is given in greater detail by Gandin (1963), and Bretherton, Davis and Fandry (1976).

The objective analysis system reads the observational data and the first-guess field. The observational data read were provided by the 92 CTD profiles from the GIN '86 cruise data, and the Levitus climatology was used as a first-guess field. An  $0.5^\circ \times 0.5^\circ$

grid from 9°W to 1°W longitude and from 60°N to 63.5°N was chosen to generate interpolated temperature values at the grid points using the objective analysis method. The chosen area has a high density of data and quite a strong signal resulting from the Arctic front (see Fig. 3).

#### 4.2. UNIRAS INTERPOLATION METHOD

The UNIRAS software package applies three interpolation methods to data sampled irregularly in space in order to obtain data on a regular grid. The UNIRAS interpolation method does not use additional data sources such as climatology. The method is a combination of double-linear, quadratic and distance-weighting interpolations.

The *double-linear interpolation* interpolates the four closest data points to the grid point to be estimated (see Fig. 4). Firstly, the interpolated values between nearest neighbours are computed at lines of constant  $x$ ,  $x = x_0$  and  $y$ ,  $y = y_0$ :

$$z_{f_1} = z_{d_i} + \Delta(z_{d_{i+1}} - z_{d_i}), \quad (8)$$

$$y_{f_1} = y_{d_i} + \Delta(y_{d_{i+1}} - y_{d_i}), \quad (9)$$

$$x_{f_1} = x_{d_i} + \Delta(x_{d_{i+1}} - x_{d_i}), \quad (10)$$

where  $\Delta = (x_0 - x_{d_i}) / (x_{d_{i+1}} - x_{d_i})$  and  $i$  rotates through 1 to 4 cyclically.

Secondly, the pairs of values at  $x = x_0$  and  $y = y_0$  are linearly interpolated to  $(x_0, y_0)$  and the mean value  $z^{est}$  determined:

$$z_{x_0, y_0}^{est} = \frac{1}{2} \left( z_{f_1} + \frac{z_{f_3} - z_{f_1}}{y_{f_3} - y_{f_1}} (y_0 - y_{f_1}) + z_{f_2} + \frac{z_{f_4} - z_{f_2}}{x_{f_4} - x_{f_2}} (x_0 - x_{f_2}) \right). \quad (11)$$

If data points are found in only three quadrants (see Fig. 5) then only two intersections with the  $x = x_0$  and  $y = y_0$  plane can be calculated. Assuming these to be  $z_{f_1}$  and  $z_{f_2}$  the grid node is assigned the value  $z_{x_0, y_0}^{est}$ :

$$z_{x_0, y_0}^{est} = z_{f_1} + \frac{z_{f_2} - z_{f_1}}{x_{f_2} - x_{f_1}} (x_0 - x_{f_1}). \quad (12)$$

If data points are found in only two adjacent quadrants then only one intersection with the  $x = x_0$  or  $y = y_0$  plane can be calculated. This value is assigned to the grid point. If data points are found in two opposite quadrants or only in one quadrant then the nearest data point is assigned to the grid node.

The *quadratic interpolation* provides another estimate of the field but one with smoothly-changing gradients. Let  $R_1$  be the distance from the grid point to the

closest data point in grid cell units,  $R_2 = 1.25R_1$ , and  $z_1$  and  $z_2$  be the average value of data points at grid distances  $R_1$  and  $R_2$ . Then  $z_{x,y}^{new}$  is the estimate value at grid node  $(x, y)$ , for  $z_{x,y}^{old}$  see Eq. (11):

$$z^{int} = R_2^2 z_1 - R_1^2 z_2 / R_2^2 - R_1^2, \quad (13)$$

$$z_{x,y}^{new} = z_{x,y}^{old} + 0.15(z^{int} - z_{x,y}^{old}). \quad (14)$$

The constants 1.25 and 0.15 are default factors.

Finally the *distance-weighting interpolation* uses an inverse distance function. The weight of the grid point in the centre is proportional to the  $1/d^r$  of the four surrounding grid points. In the current version of UNIRAS the parameter  $r = 3$  (UNIRAS, 1986).

The UNIRAS interpolation method reads the GIN '86 observational data and generates interpolated values at the grid points using each of the methods described above, and these are then simply averaged to produce the final estimate of the grid point value (for more details see UNIRAS, 1986). The resulting regular temperature fields are located on a  $0.5^\circ \times 0.5^\circ$  grid from  $9^\circ W$  to  $1^\circ W$  longitude and from  $60^\circ N$  to  $63.5^\circ N$  latitude.

## 5. Results

Following software implementation, high-resolution regularly-gridded maps of the GIN '86 temperature data were derived using the two different analysis methods described above. From the AOG database, where the 92 CTD profiles of the GIN '86 data were stored, the temperature data sets were extracted for depth levels of 10 m, 50 m, 100 m, 150 m, 200 m. These depth levels were considered representative for constructing the mesoscale thermal field of the upper oceanic layer of the area of interest. This area was from  $-9^{\circ}\text{W}$  to  $-1^{\circ}\text{W}$  longitude and  $60^{\circ}\text{N}$  to  $63.5^{\circ}\text{N}$  latitude. The measured temperature values are displayed at the corresponding CTD locations as colour dots in Figs. 5a-9a. (A colour scale of the temperature values is included in each of the figures.) The Levitus climatological temperature data interpolated on a  $0.5^{\circ} \times 0.5^{\circ}$  grid by cubic splines are shown in Figs. 5b-9b. In all the selected depth levels we notice south-north structured gradients that reveal the southern edge of the Arctic front.

Comparing the GIN '86 data (Figs. 5a-9a) and the Levitus climatological data (Figs. 5b-9b), we notice marked differences in the thermal variability. The CTD data points, plotted as individual dots to highlight the sampling distribution, reveal the presence of a cold intrusion from the north ( $T < 6.5^{\circ}\text{C}$  at 100 m; see the blue dots in Fig. 7a) into the relatively warm North Atlantic waters ( $T > 7.0^{\circ}\text{C}$  at 100 m). This is absent in the climatology (Fig. 7b). Such intrusions and eddies are known to have lifetimes of only a few weeks and dimensions of 50-150 km, and also suffer from interannual variability, so that a climatology representing a seasonal average of many years over a  $1^{\circ} \times 1^{\circ}$  area cannot reproduce them. Also at 100 m depth, the CTD data show warm Atlantic water (yellow dots in Fig. 7a) extending northwards at the eastern edge of the domain, i.e. along the edge of the Shetland Shelf, whereas the climatological data show this warm water ( $T > 8.5^{\circ}\text{C}$  at 100 m; Fig. 7b) failing to reach the southeastern corner of the domain.

We may also note that the entire CTD survey took approximately 3 weeks to complete, so strictly speaking it is not an instantaneous sample of the thermal field. Where the measurements have been repeated after a couple of weeks along the same track running from  $6^{\circ}$  to  $2^{\circ}\text{W}$  and  $60.5^{\circ}$  to  $62^{\circ}\text{N}$  (roughly along the diagonal of the plot), significant variations can already be noticed (see Figs. 5a-9a).

The results of the data interpolation using the UNIRAS method are given in Figs. 5c-9c at depths of 10, 50, 100, 150 and 200 m. The corresponding results with the objective analysis method are given in Figs. 5d-9d. From these figures we see that, in regions where there is a high density of data the agreement between the two methods is good. However, in data-sparse regions, such as the northwest corner of the domain, to the north and west of the Færø Islands ( $\sim 62^{\circ}\text{N}$ ,  $\sim 6^{\circ}\text{W}$ ), there

are significant differences. Again, using the 100 m data as an example (Figs. 7c and 7d), the objective analysis method produces predominantly zonal contours, whereas those from the UNIRAS method are compressed into a meridional feature at the centre of the northern edge of the box. The objective analysis method, making heavy use of climatology (see Fig. 7b) where the data is sparse, thus spreads out the cold water,  $T < 6.5^\circ$ , over the whole northern quarter of the region, whereas the UNIRAS method, relying on weighted extrapolation, describes a 'tongue' of cold water between  $5^\circ\text{W}$  and  $2^\circ\text{W}$  at all depth levels. The southernmost tip of the narrow tongue (defined by  $T < 5.5^\circ\text{C}$  at 100 m depth) reaches  $\sim 62.4^\circ\text{N}$  in the UNIRAS analysis results, but reaches only  $\sim 63.0^\circ\text{N}$ , as a broad feature, in the objective analysis results. The situation at 100 m depth in the southeastern corner is also markedly dissimilar in the two representations. The UNIRAS method, following the CTD data (Fig. 7a), makes the  $8.5^\circ\text{C}$  contour meander to the northeast leaving the domain at  $61.5^\circ\text{N}$ ,  $1^\circ\text{W}$ , whereas the objective analysis method, following the climatology (Fig. 7b), has it going due south along the  $2^\circ\text{W}$  meridian.

When the data density is low the objective analysis method is dominated by the climatology in use. The UNIRAS method in data-sparse areas extrapolates a smoother field from the data.

## 6. Discussion and conclusions

Two interpolation methods have been presented in this report that produce regularly-gridded maps of a field (in this case, temperature) for the Greenland-Iceland-Norwegian Sea area for use by numerical environmental and acoustical models. The two methods are based on different mathematical principles and one uses an additional source of information (climatology) but their products agree for the temperature field in areas of dense data coverage.

The primary factor affecting the quality of both analysis methods seems to be the quantity of data available. In practice the quantity of data available for an operational analysis will usually be quite limited. The use of additional information helps to overcome this problem, and the objective analysis method has the ability to utilise additional independent information, e.g. climatology, to produce an improved analysis. An important factor for the good performance of the objective analysis theory is the choice of climatology. The results presented here also show that when the large-scale structure of the data and of the climatology do not agree (i.e. when the field sampled by the data has significant departures from the climatological mean field) the objective analysis method can give rise to anomalous horizontal gradients in going from the regime dominated by data to that dominated by climatology. Such an example can be seen in the south-east corner of our area of interest at 100 m depth.

In oceanography there is always the problem of inadequate data sampling. Generally in an observational data set there will be large data gaps or significant elapsed time. However, although the observational data coverage in this analysis (92 CTD profiles sampled over a period of 3 weeks covering an area from  $9^{\circ}$  to  $1^{\circ}$ W and  $60^{\circ}$  to  $63.5^{\circ}$ N) is denser than for many oceanographic applications, a definite comparison between the two methods cannot be made. In areas of inadequate data coverage the output of the methods gives rise to discrepancies. The application will dictate which type of error or uncertainty can be tolerated (i.e. whether spurious gradients are more tolerable than a fictitious extrapolated field). In our experience the objective analysis scheme *cannot* be applied to all situations without exercising some degree of caution in the interpretation of the output field. A more definite study should be made in the future using perhaps a synthetic field or even high-resolution satellite imagery.

We also plan to compare similar analyses using different climatologies, such as the Generalized Digital Environmental Model (GDEM) climatology, and to develop a climatological database from all AOG cruises and other available data in the GIN Sea area.



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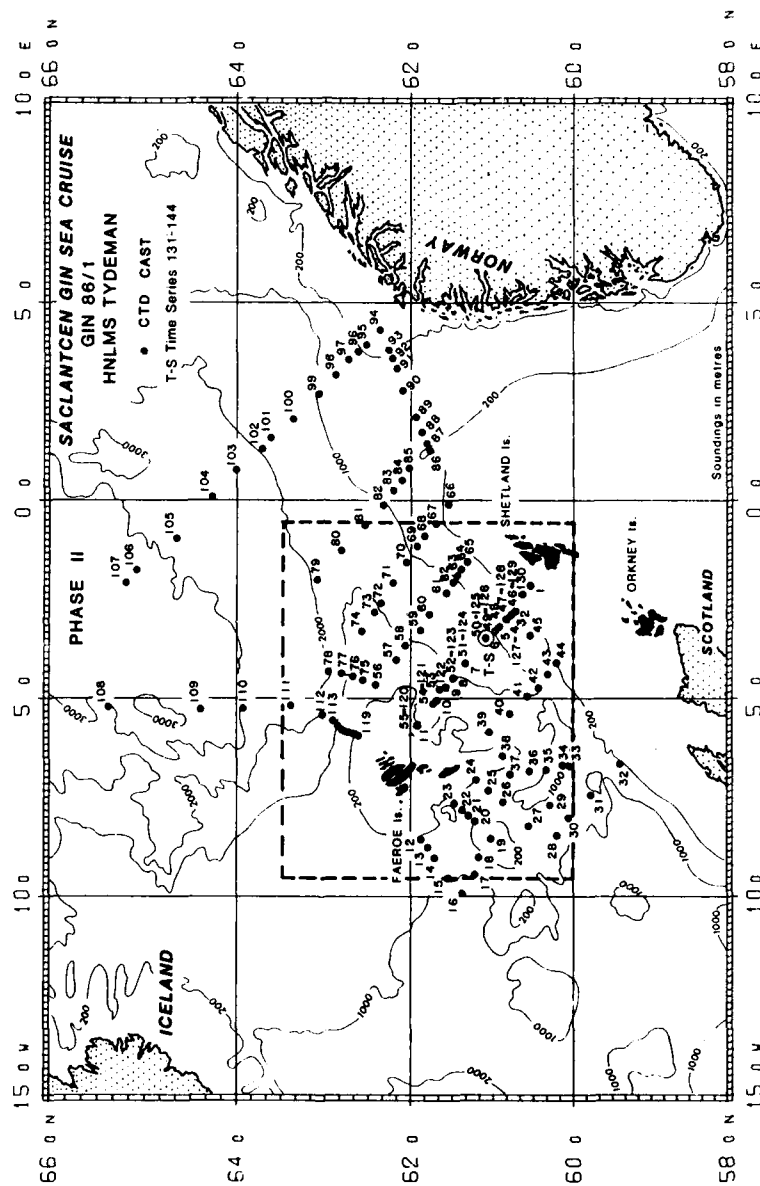


Fig. 1. GIN '86 cruise data distribution. The dots represent CTD casts taken during the June of '86, and the numbering of the stations is according to the order of sampling. The box marks the research area covered in this study.

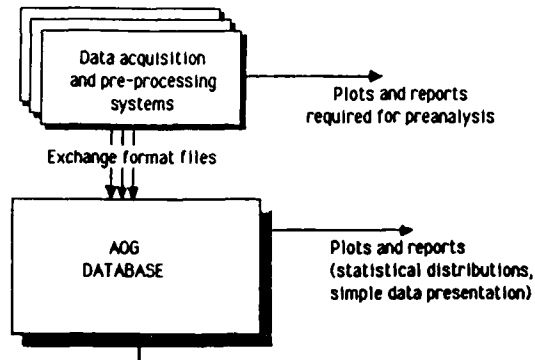


Fig. 2a. Data acquisition and database plan.

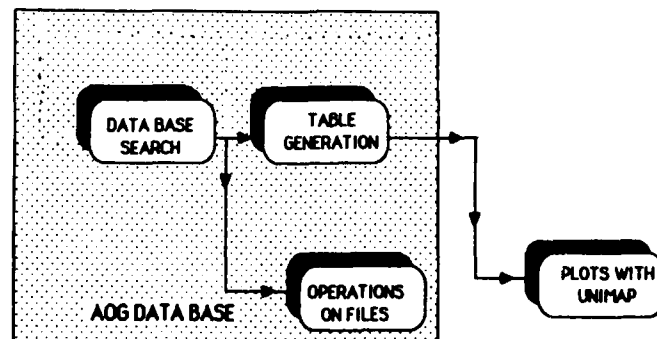


Fig. 2b. Database plan diagram.

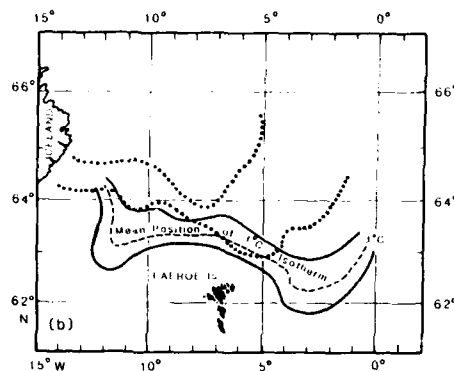


Fig. 3. Location of the Arctic Front over the Iceland-Faroe Ridge. The mid-gradient isotherm envelope at 300 m (solid), at 100 m (dotted) and the mean position of the 3° isotherm at 300 m (dashed).

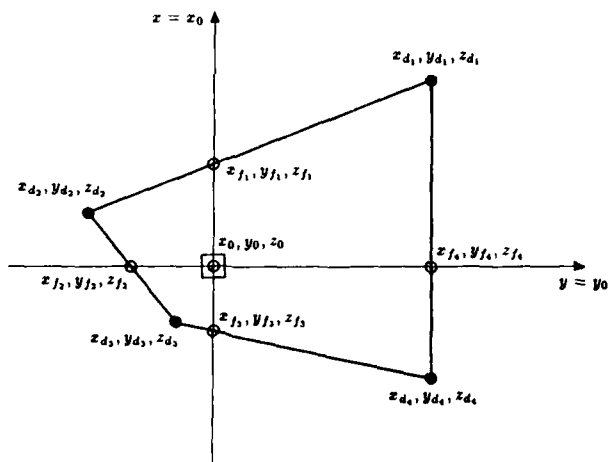


Fig. 4. UNIRAS interpolation method grid scheme.

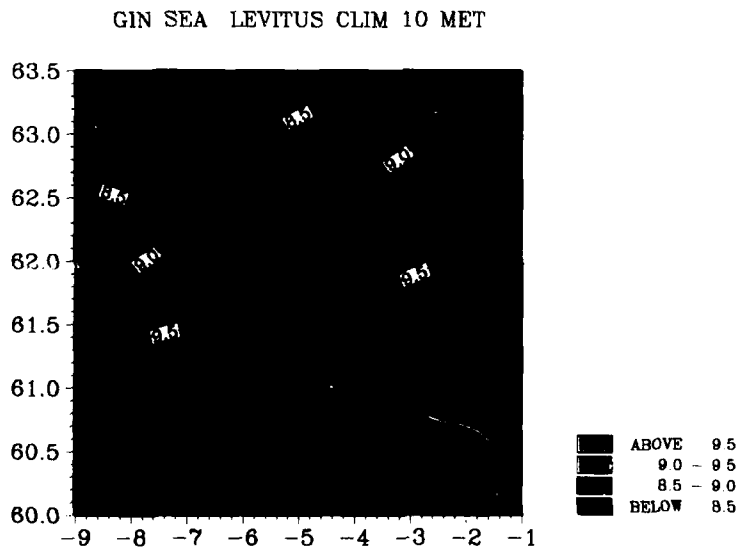
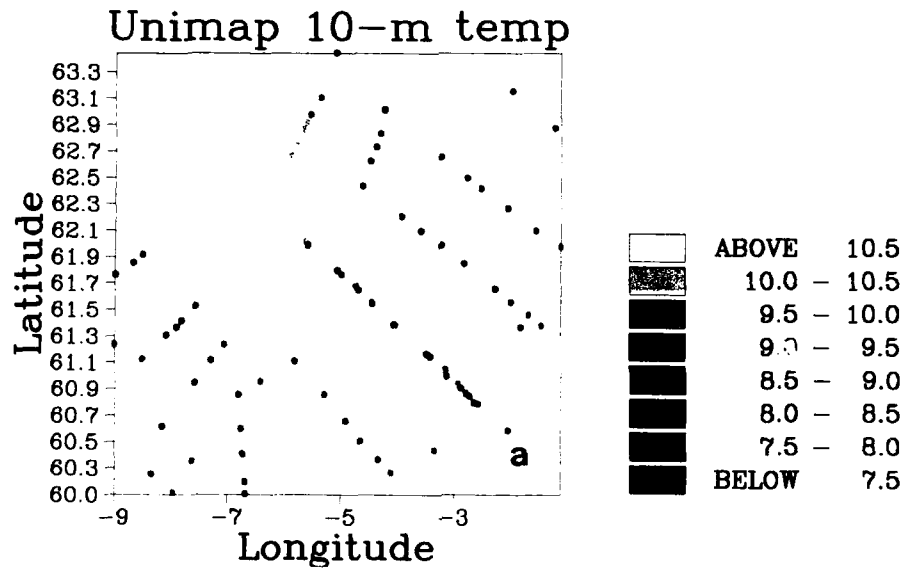


Fig. 5. (a) Temperature measurements at 10 m depth from the GIN '86 data. (b) Temperature field obtained from the Levitus climatology at 10 m depth.

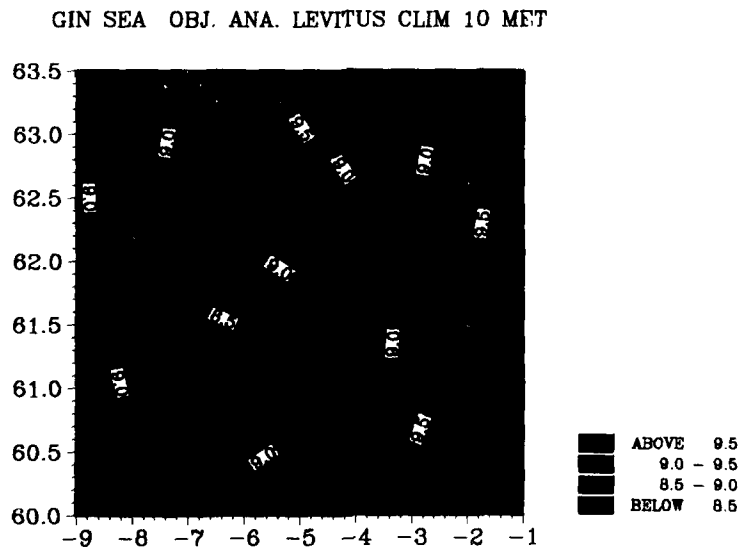
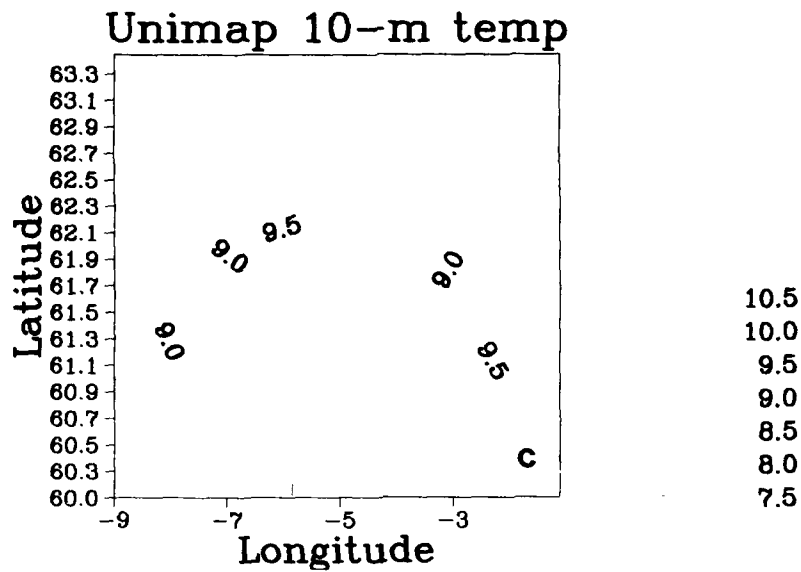


Fig. 5 cont'd. Thermal analysis resulting from (c) the UNIRAS interpolation and (d) the objective analysis interpolation using the GIN '86 data and Levitus climatology for 10 m depth.

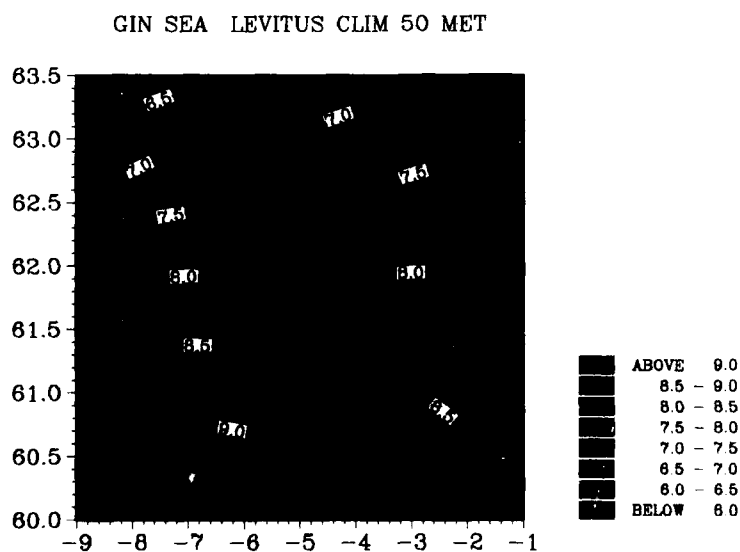
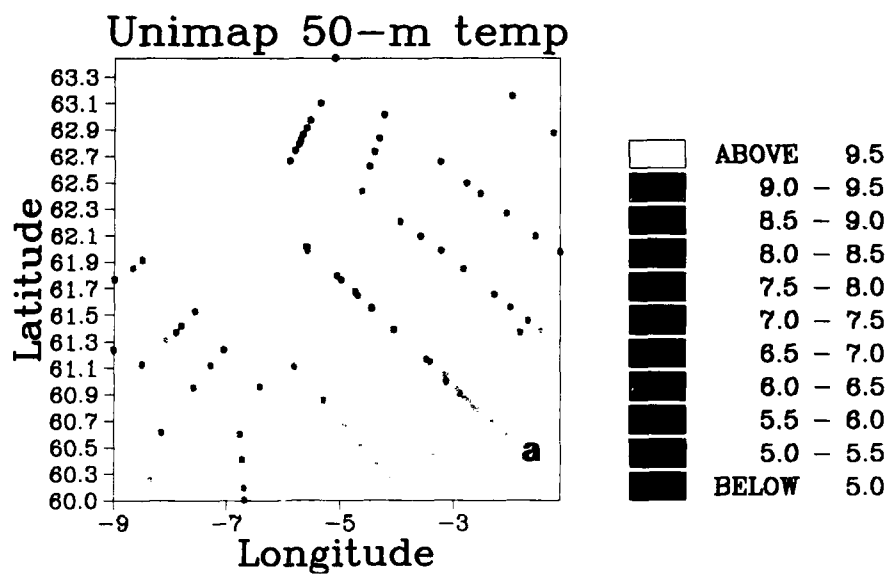
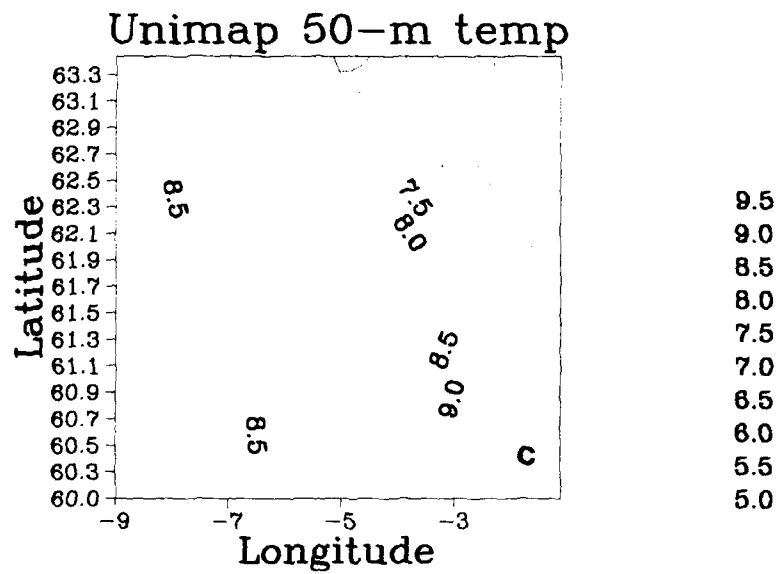


Fig. 6. (a) Temperature measurements at 50 m depth, from the GIN '88 data. (b) Temperature field obtained from the Levitus climatology at 50 m depth.



GIN SEA OBJ. ANA. LEVITUS CLIM 50 MET

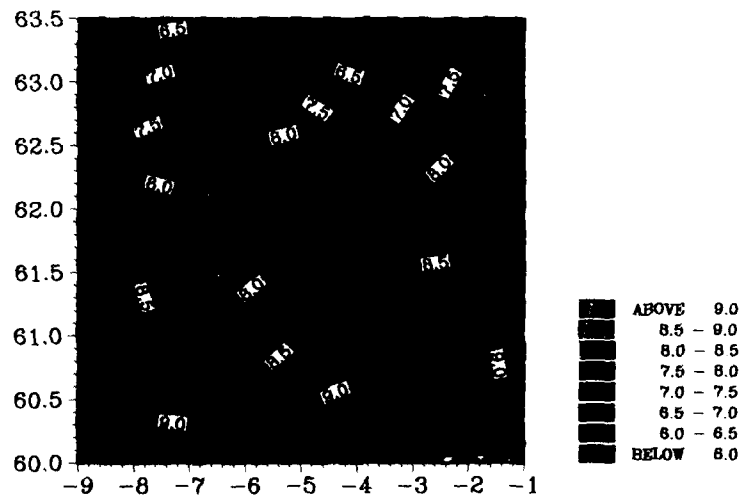


Fig. 6 cont'd. Thermal analysis resulting from (c) the UNIRAS interpolation and (d) the objective analysis interpolation using the GIN '86 temperature data and Levitus climatology for 50 m depth.



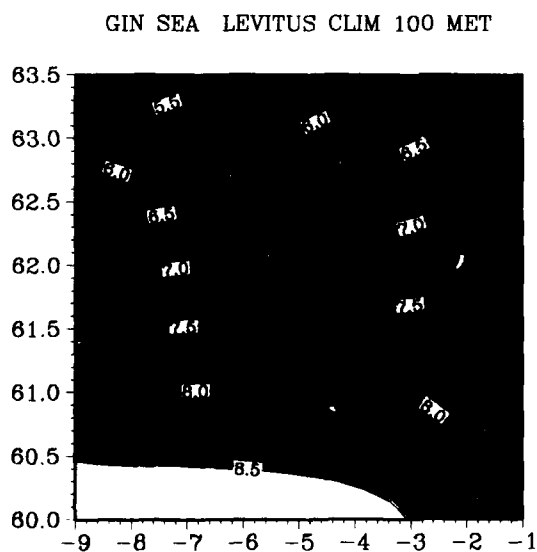
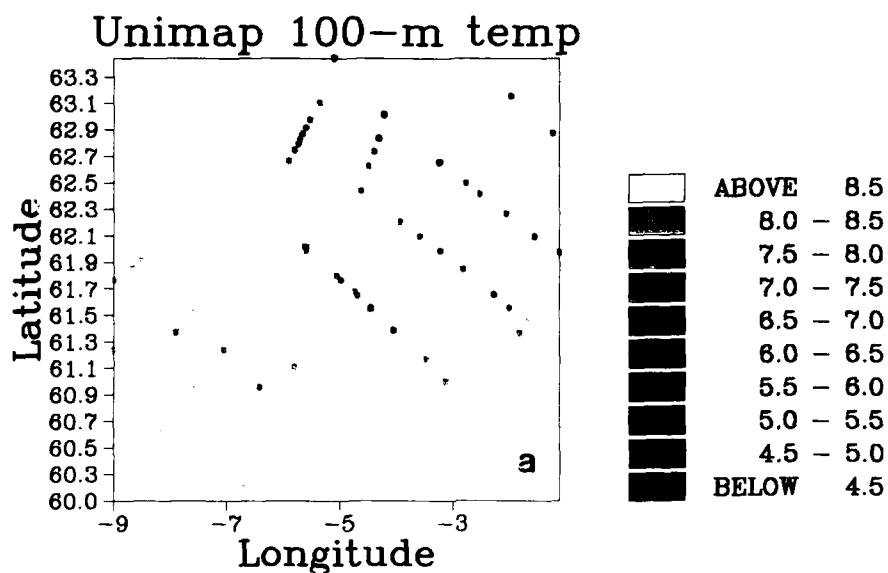
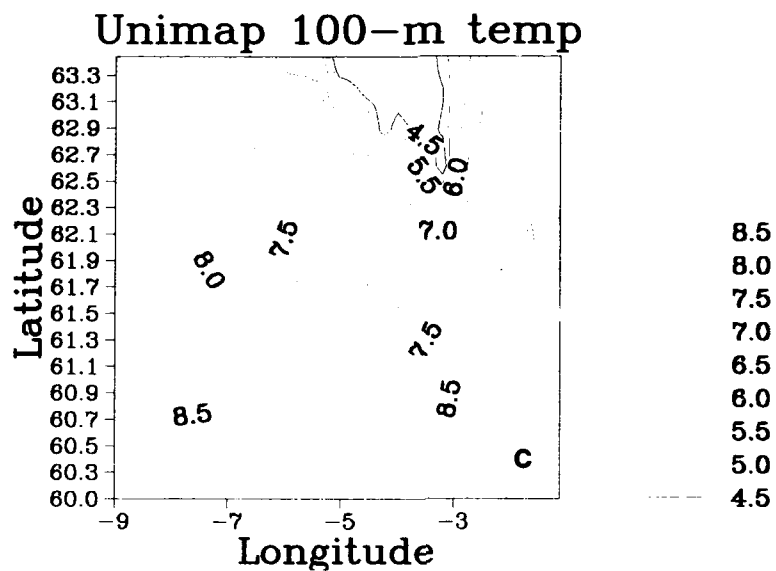


Fig. 7. (a) Temperature measurements at 100 m depth, from the GIN '86 data. (b) Temperature field obtained from the Levitus climatology at 100 m depth.



GIN SEA OBJ. ANA. LEVITUS CLIM 100 MET

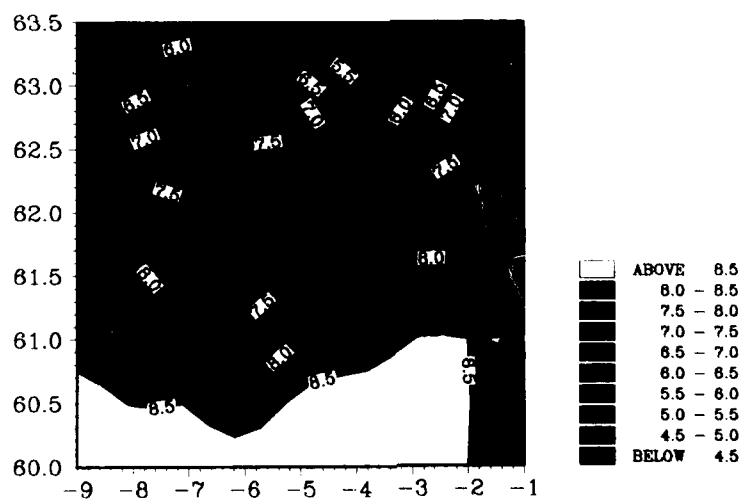


Fig. 7 cont'd. Thermal analysis resulting from (c) the UNIRAS interpolation and (d) the objective analysis interpolation using the GIN '86 data and Levitus climatology for 100 m depth.

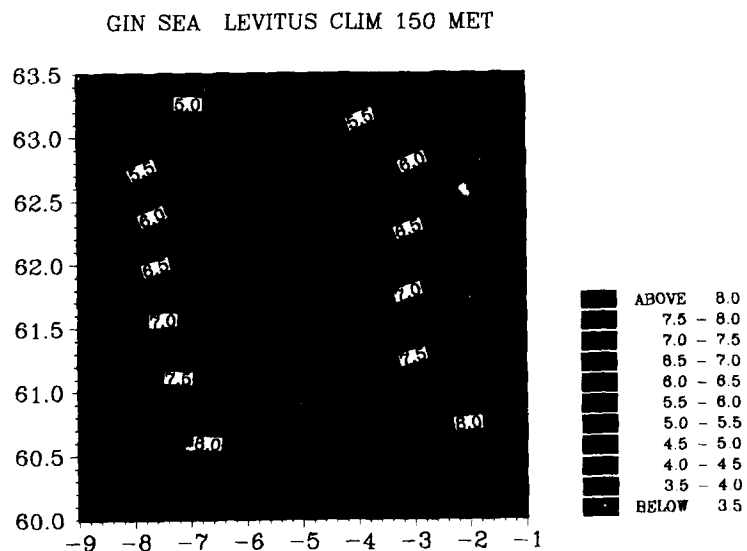
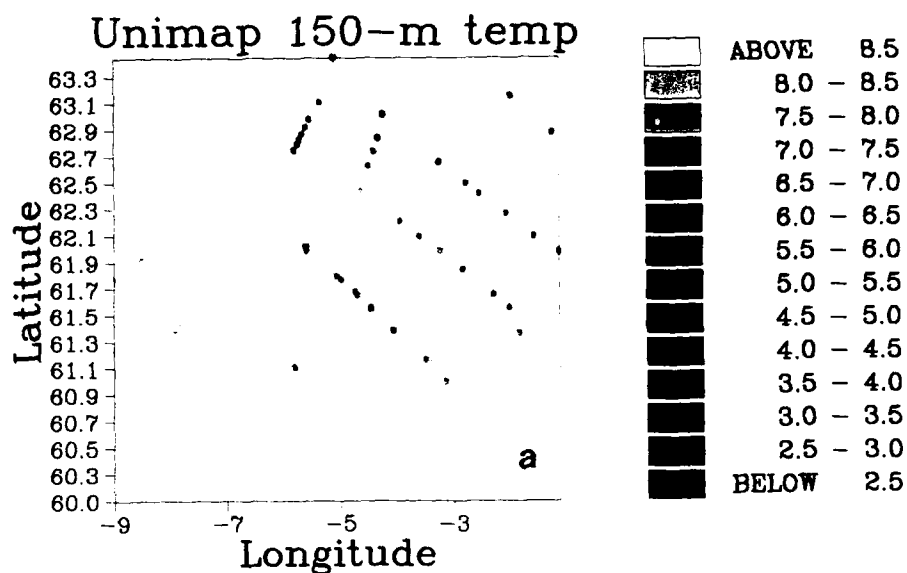
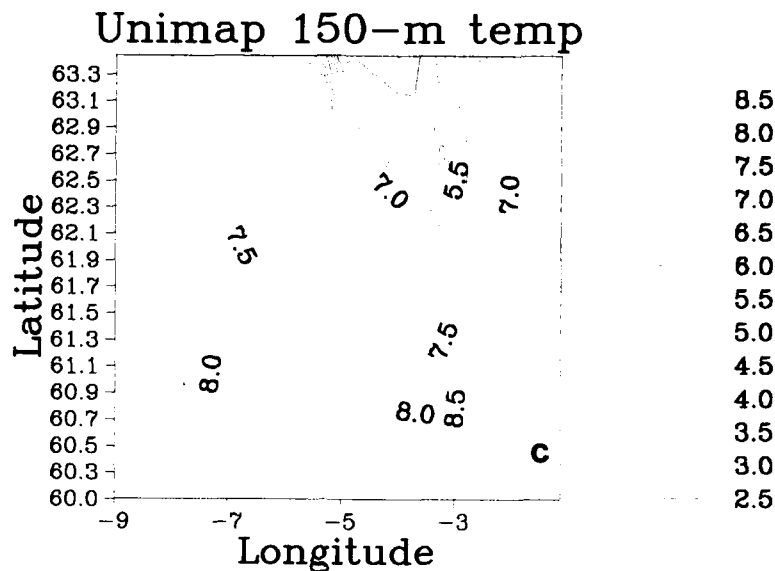


Fig. 8. (a) Temperature measurements at 150 m depth, from the GIN '86 data. (b) Temperature field obtained from the Levitus climatology at 150 m depth.



GIN SEA OBJ. ANA. LEVITUS CLIM 150 MET

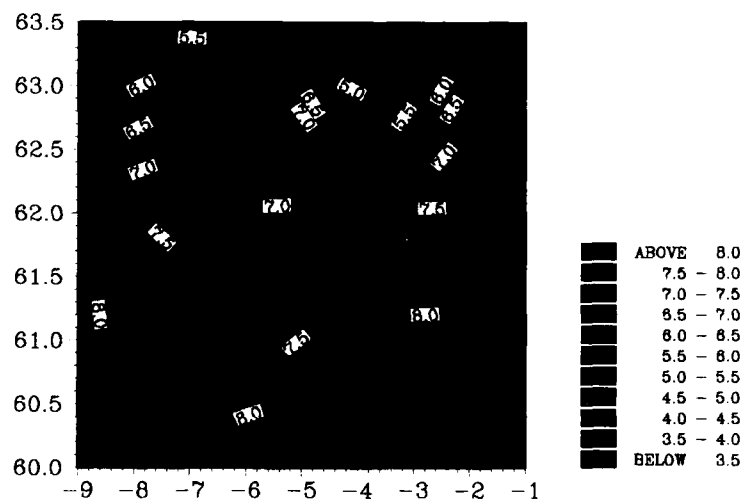


Fig. 8 cont'd. Thermal analysis resulting from (c) the UNIRAS interpolation and (d) the objective analysis interpolation using GIN '86 data and Levitus climatology for 150 m depth.

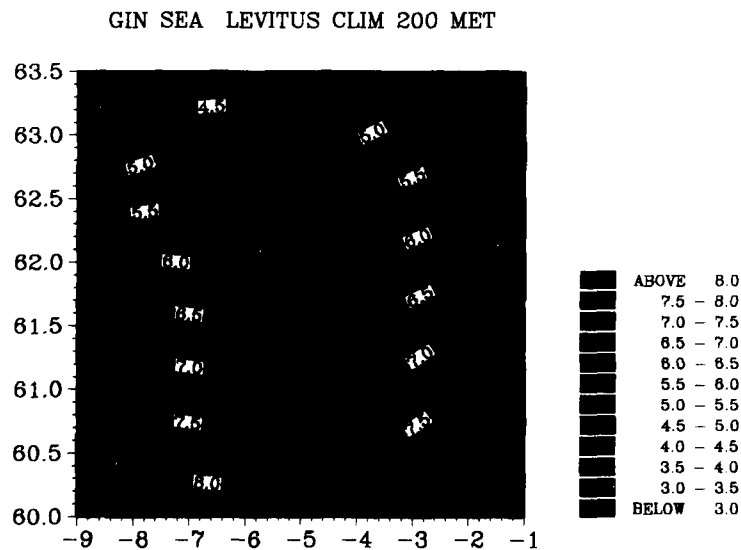
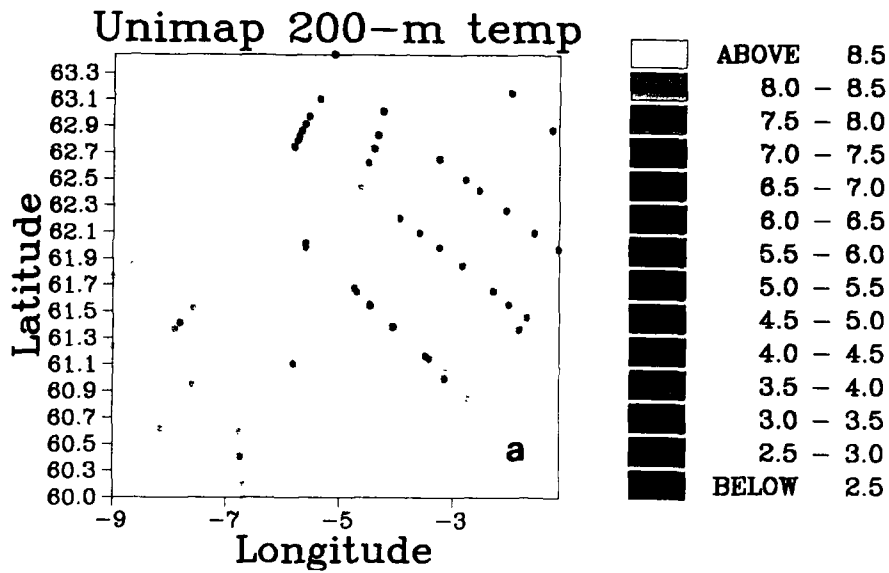
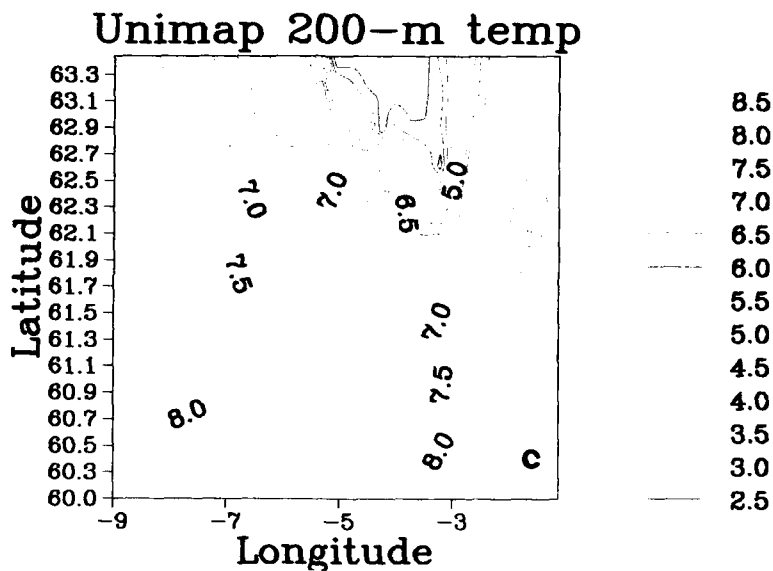


Fig. 9. (a) Temperature measurements at 200 m depth, from the GIN '86 data. (b) Temperature field obtained from the Levitus climatology at 200 m depth.



GIN SEA OBJ. ANA. LEVITUS CLIM 200 MET

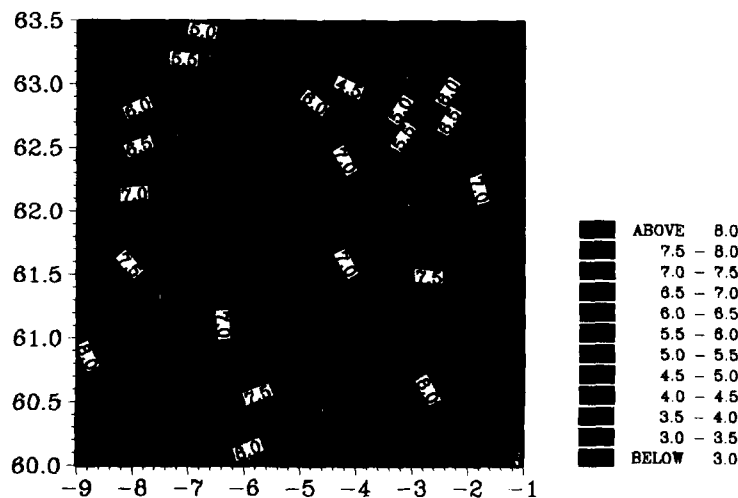


Fig. 9 cont'd. Thermal analysis resulting from (c) the UNIRAS interpolation and (d) the objective analysis interpolation using GIN '86 data and Levitus climatology for 200 m depth.

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